RENDERING

TOM CLANCY'S RAINBOW SIX® | SIEGE

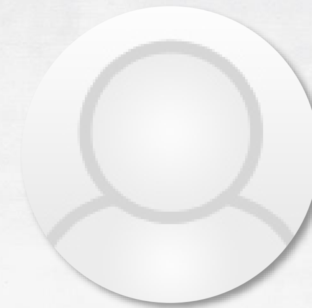
Jalal El Mansouri
Technical Architect
Ubisoft Montréal

RAINBOW SIX
3D TEAM

Alan Quayle

Jalal El Mansouri

Pierre-Marc Bérubé


Zhuo Chen

Benjamin Rouveyrol

John Huelin

Yoann Rocagel

AGENDA

- RAINBOW RENDERER OVERVIEW
- MATERIAL BASED DRAW CALL SYSTEM
- CHECKERBOARD RENDERING

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- **Rebirth** of a loved franchise that is precious to a lot of hard-core gamers
- **Gameplay** driven
- **Destruction** as a core gameplay mechanic
  - Destruction must be consistent between platforms
- First Rainbow Six shipping with the **engine**
  - Lots of legacy code from previous prototypes

SIEGE TECH MISSION

- Targeting **60FPS**:
  - GPU : 14ms average on non combat situations
  - CPU : Max 38ms linear time on CPU (consoles)
- Provide scalable destruction

- Ship at a higher resolution than 720p on all consoles
- Commit to 4K on PC at a decent framerate

- Provide a strong PC version on a console oriented production
  - Fitting on 1GB of RAM becomes a challenge with current gen

SIEGE IS A **LIVE GAME**

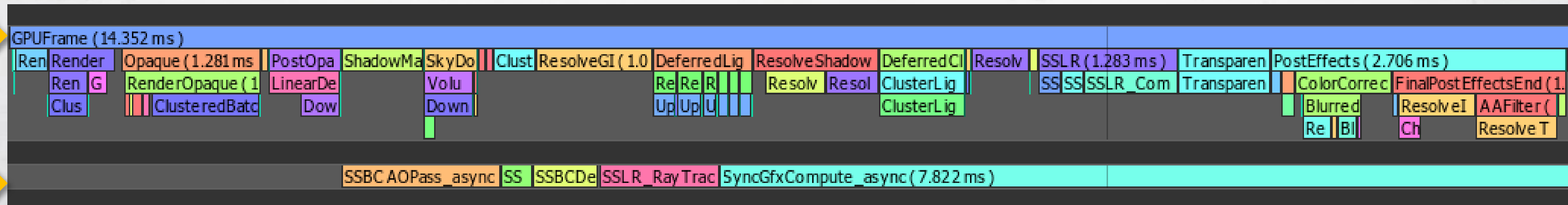
- Graphics features can be continually iterated on
- Test new tech to improve look or comfort
  - Auto-exposure for players
- Be careful not to break things!

SIEGE FRAME

- Hierarchical view of a GPU frame
  - Average 5ms spent on geometry rendering
    - Heavy use of culling!
    - Shadow caching!
  - Average 5ms spent on lighting (SSR included)
    - Checkerboard rendering helps!
    - SSAO & SSR ray trace done in async
  - Average 4ms spent on post processing/other full screen processing

GRAPHIC PIPE

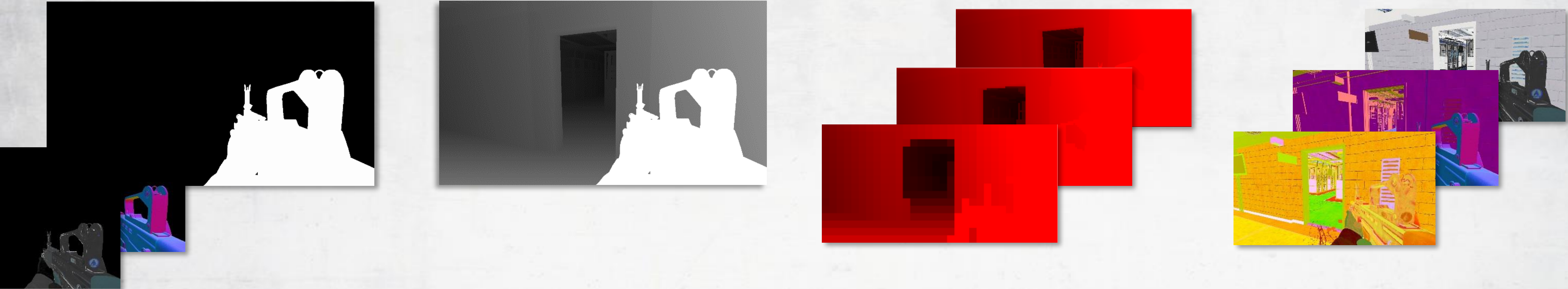
ASYNCH PIPE



SIEGE FRAME

- Hierarchical view of a CPU critical path
  - 10ms avg on the critical path
    - All passes and tasks able to fork and join to minimize critical path
    - Shadow caching!
  - Max 4ms linear spent on opaque pass
    - Material based draw call system!

OPAQUE RENDERING



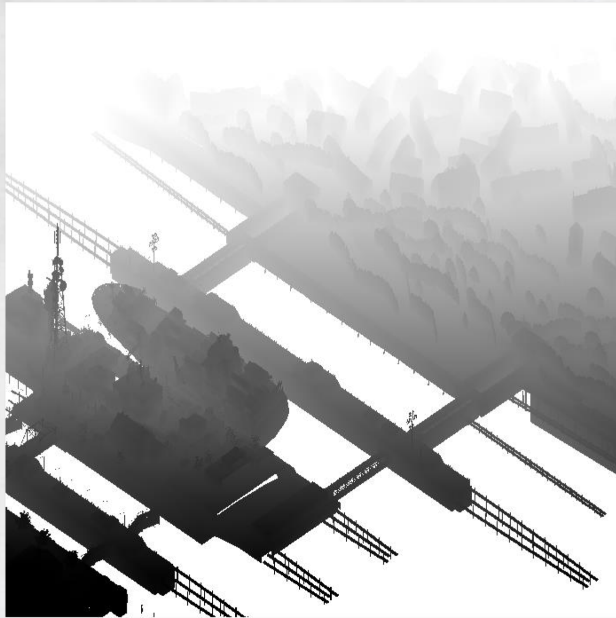
First person rendering → 400 best occluders to depth buffer → Generate Hi-Z → Opaque culling & rendering

SHADOW RENDERING

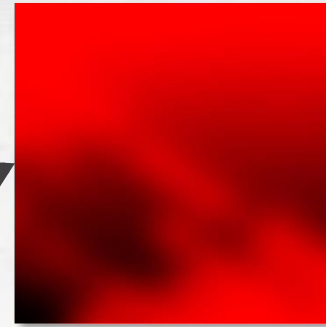
- All shadows are cache based
  - Use cached Hi-Z for culling
- Sunlight shadow done in full resolution
  - Separate pass to relieve lighting resolve VGPR pressure
  - Uses Hi-Z representation of the cached shadow map to reduce the work per pixel
- Local lights are resolved in a quarter resolution
  - Resolved results stored in a texture array
  - Lower VGPR usage on light accumulation
  - Bilateral upscale

SHADOW RENDERING – SUN / MOON

- Shadow map containing all static objects built on load



6Kx6K 16bit



512x512 ESM

Hi-Z

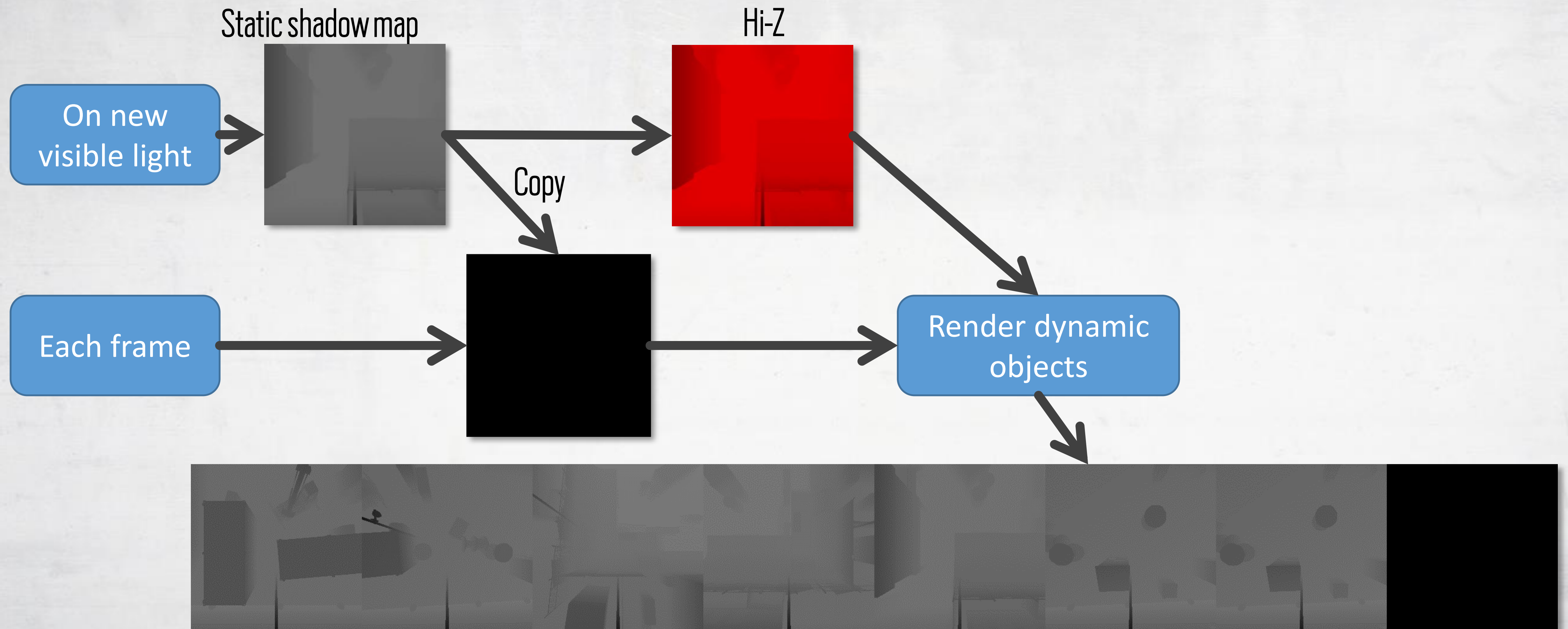
SHADOW RENDERING – SUN / MOON

- Ability to scale shadow cost by mixing cascades with static map
  - Static Hi-Z shadow map always used for dynamic object culling

- On Xbox One :
  - 1st cascades are fully dynamic (not enough resolution with 6K)
  - 2nd and 3rd cascades renders dynamic objects only and blend with the static shadow map
  - 4th cascade is substituted by the static shadow map

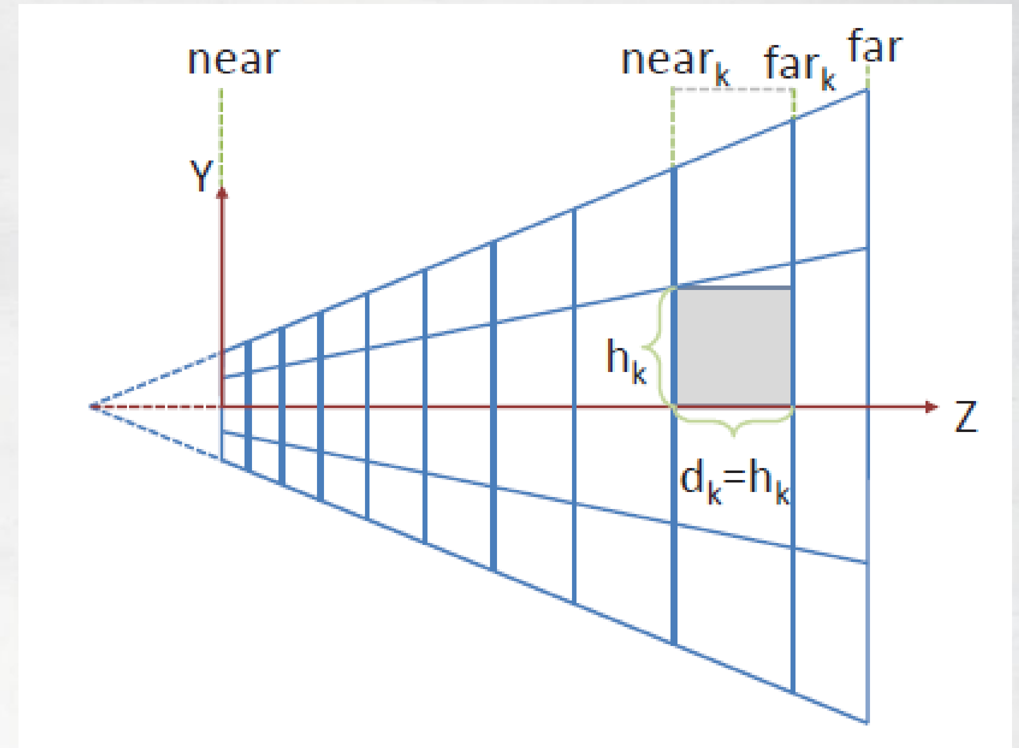
SHADOW RENDERING – LOCAL PROJECTORS

- We handle a maximum of **8** visible shadowed local lights



LIGHTING

- Uses a clustered structure on the frustum:
  - 32x32 pixels based tile
  - Z exponential distribution
- Hierarchical culling of light volume to fill the structure
- Local cubemaps regarded as lights
- Shadows, cubemaps and gobos reside in textures arrays
  - Deferred uses pre-resolved shadow texture array
  - Forward uses shadows depth buffer array



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RAINBOW SIX **DESTRUCTION**

ART DIRECTION

- When destruction happens you need to feel that something big went on!

FLOORS & WALLS

- Procedurally generated unique geometry
- Poking holes degrades occlusion efficiency

DESTRUCTIBLE PROPS & DEBRIS

- Generally smaller meshes but in great numbers
- Can be instanced or unique

ROUND 1

UNIQUE GEOMETRY

MAIN BUILD

100

LB

99

99

RB

2F
Walk-in

BREACHING ROUND
1/199

100s OF DEBRIS
ROUND 1
MAIN BUILD
100
2F
Walk-in
BREACHING ROUND
1/199

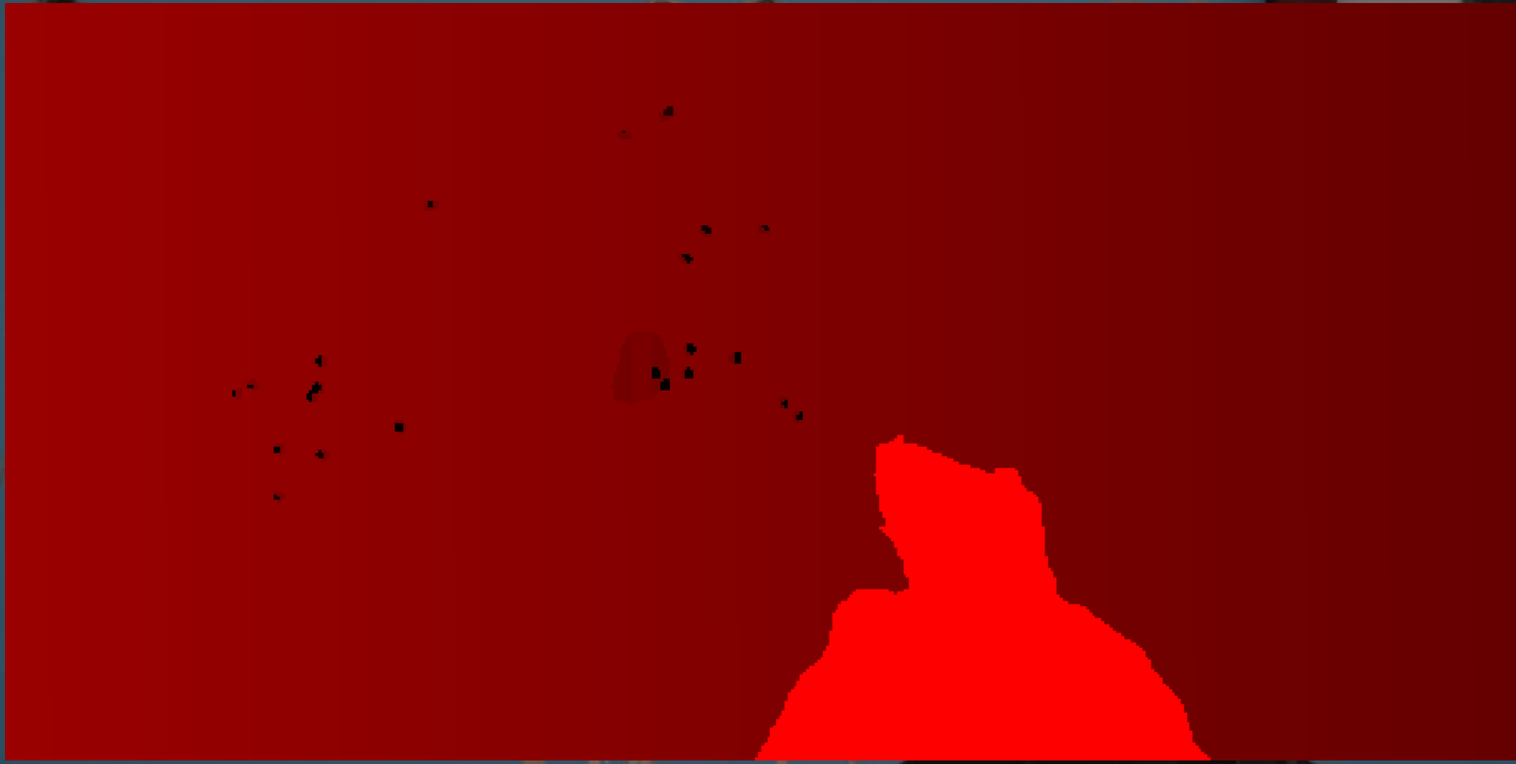
MAIN BUILD
0.1.0
RELOAD
100

3

2
2

2F
Bathroom
P226 Mk 25
2/30

MAIN BUILD
0.1.0



100

LB

3

2

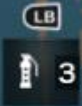
RB

2

2F
Bathroom

P226 Mk 25
2/30

MAIN BUILD
0.1.0

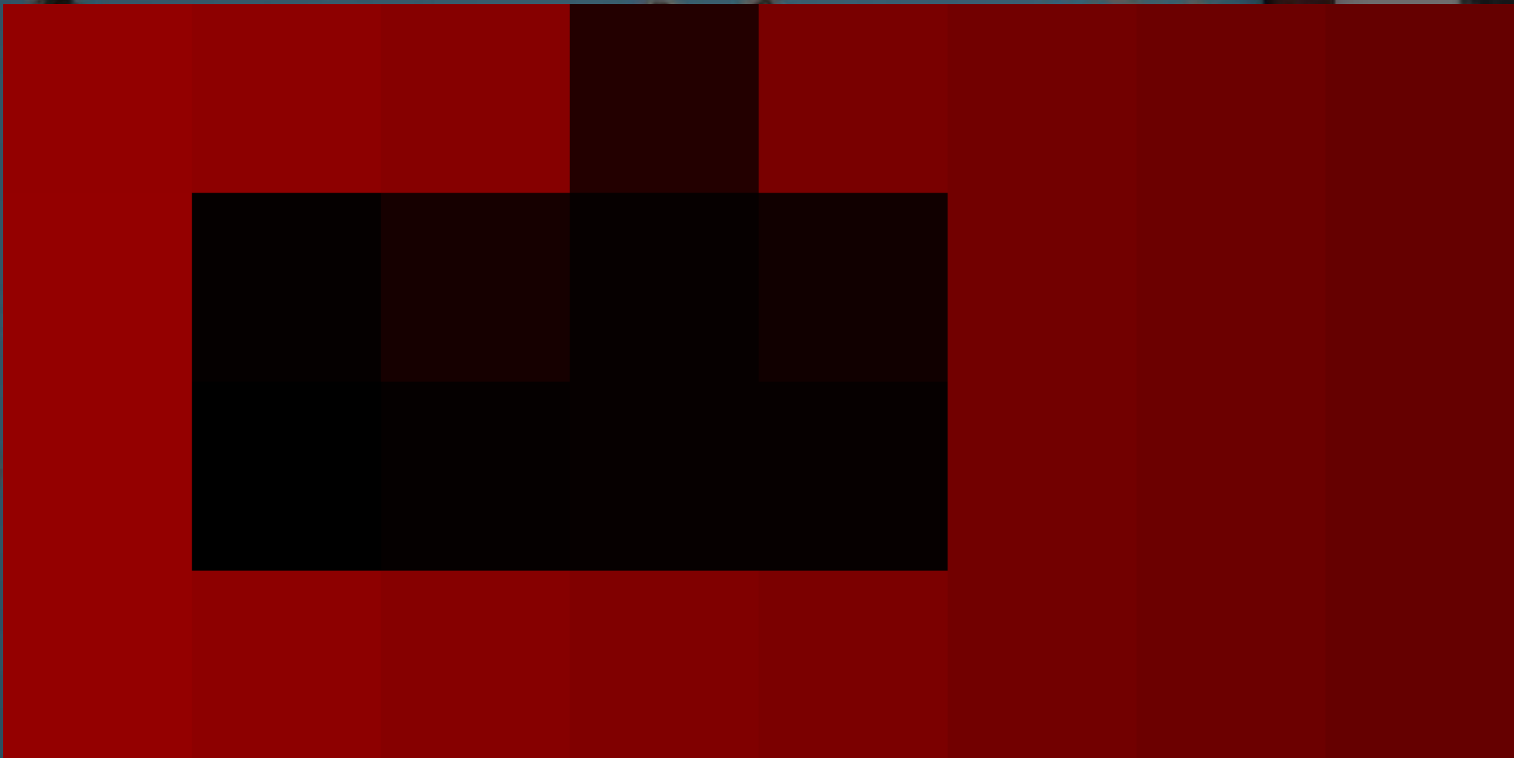
100

3

2

2

2F
Bathroom
P226 Mk 25
2/30

MAIN BUILD
0.1.0



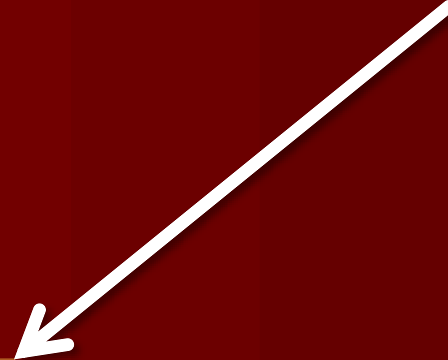
100

3

2
2

2F
Bathroom

P226 Mk 25
2/30



A PROP **AABB** THIS BIG WILL FAIL OCCLUSION TEST

RAINBOW SIX **DESTRUCTION**

- Early prototypes were largely graphic bound (CPU and GPU) on average
- PC DX11 deferred contexts aren't that great at scaling
- Material based draw call system
  - Materials define destruction properties
  - Debris share material
  - See [Haar&Altonen15]
- In need of granularity in culling to keep up with destruction

UNIFIED BUFFERS

- A lot of resources in Rainbow Six reside in an unified buffer of some sort:
  - Unified Vertex Buffer
  - Unified Index Buffer
  - Unified Constant Buffer
  - ...
- Structured buffers built on top of raw buffers with auto generated code:
  - Using C++ data descriptors for GPU unified data
  - Meta data passed on to specify access pattern

UNIFIED BUFFERS - CONSTANT

```
// Cpp Code
void EntityConstantBufferBridge::CreateDescriptor(ConstantBufferDescriptor* descriptor )
{
    popBeginMapShaderParametersAndSetUsage(EntityConstantBufferBridge, descriptor, Entity);
    popMapShaderParameter("g_NodeWorld",        m_WorldMatrix);
    popMapShaderParameter("g_InvScaleSqr",      m_InvScaleSqr);
}
// --
// ...
// HLSL GeneratedCode
ByteAddressBuffer g_UnifiedConstantBuffer;
void LoadEKInstanceProvider(uint index)
{
    uint offset = Mad_U24(index, EKINSTANCEPROVIDER_STRIDE, EKINSTANCEPROVIDER_GLOBALBUFFER_OFFSET);
    g_NodeWorld = ToFLOAT4x4(
        g_UnifiedConstantBuffer.Load4(offset + 0x0),
        g_UnifiedConstantBuffer.Load4(offset + 0x10),
        g_UnifiedConstantBuffer.Load4(offset + 0x20),
        g_UnifiedConstantBuffer.Load4(offset + 0x30)
    );
    g_InvScaleSqr = ToFLOAT4(g_UnifiedConstantBuffer.Load4(offset + 0x40));
}
// --
```

UNIFIED BUFFERS - BENEFITS

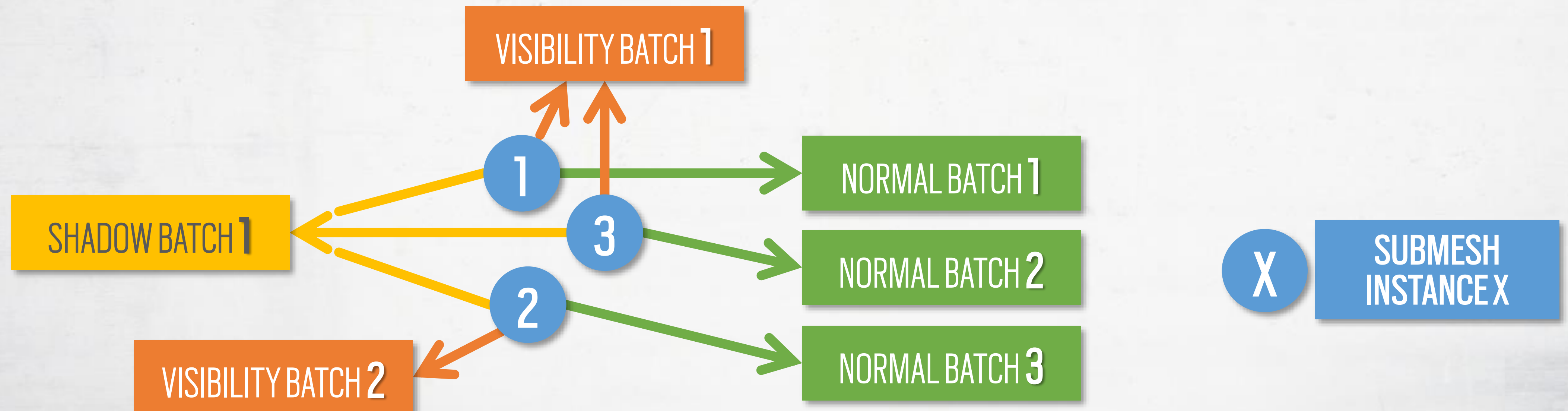
- Complete control over data layout
  - We can easily experiment with different data type accesses (AOS, SOA, Structure of u32 Arrays...)
  - Custom packing and support for new data types
- High level API supports broadcasting values
- Code auto-generation allows us to migrate to new access patterns easily

MATERIAL BASED DRAW CALLS

- Geometry and constants are unified
- A draw call is then defined by :
  - Shaders
  - Non-Unified Resources (Textures, etc…)
  - Render States (Sampler States, Raster States)
- Elements that share the above are batched together
- Passes that don't use a subset of the resources and states are further batched together

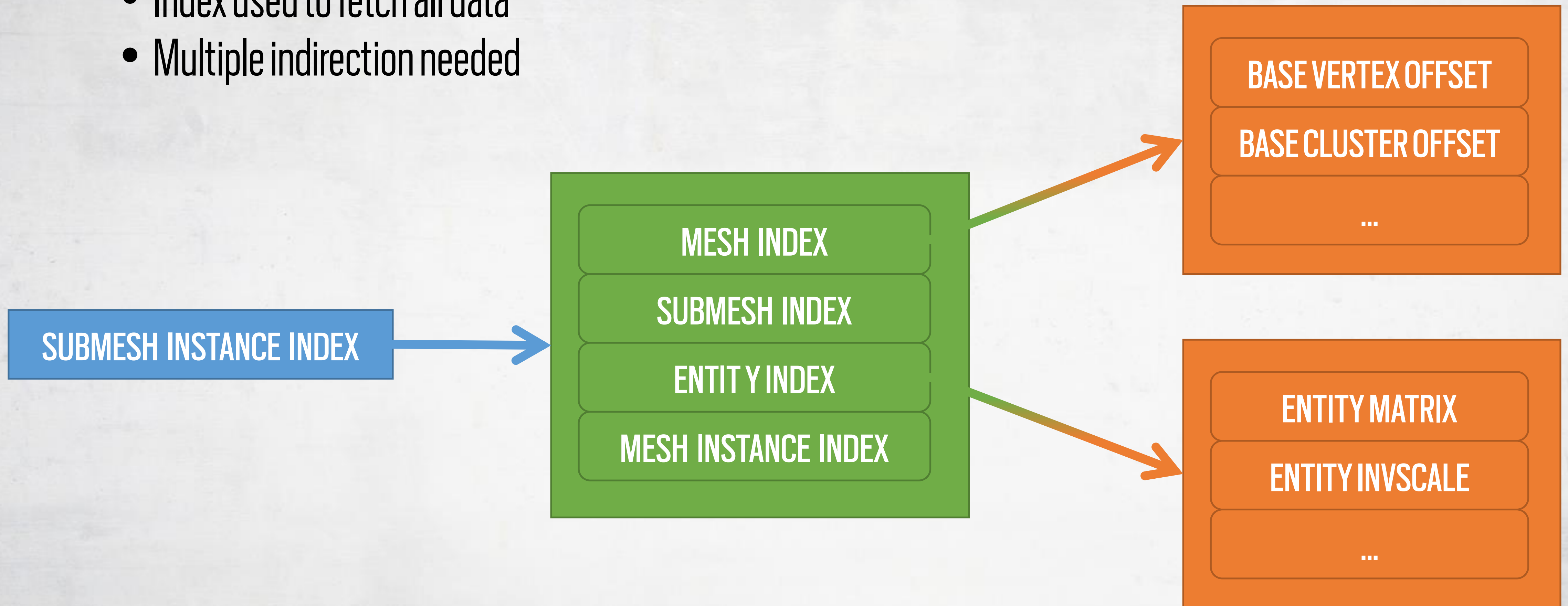
GATHERING DRAW CALLS

- On initialization, each submesh instance is mapped to 3 batches: Normal, Shadow and Visibility
- The batch types used to mask non necessary data
- Each batch will correspond to a MultiDrawIndexedIndirect command



GATHERING DRAW CALLS

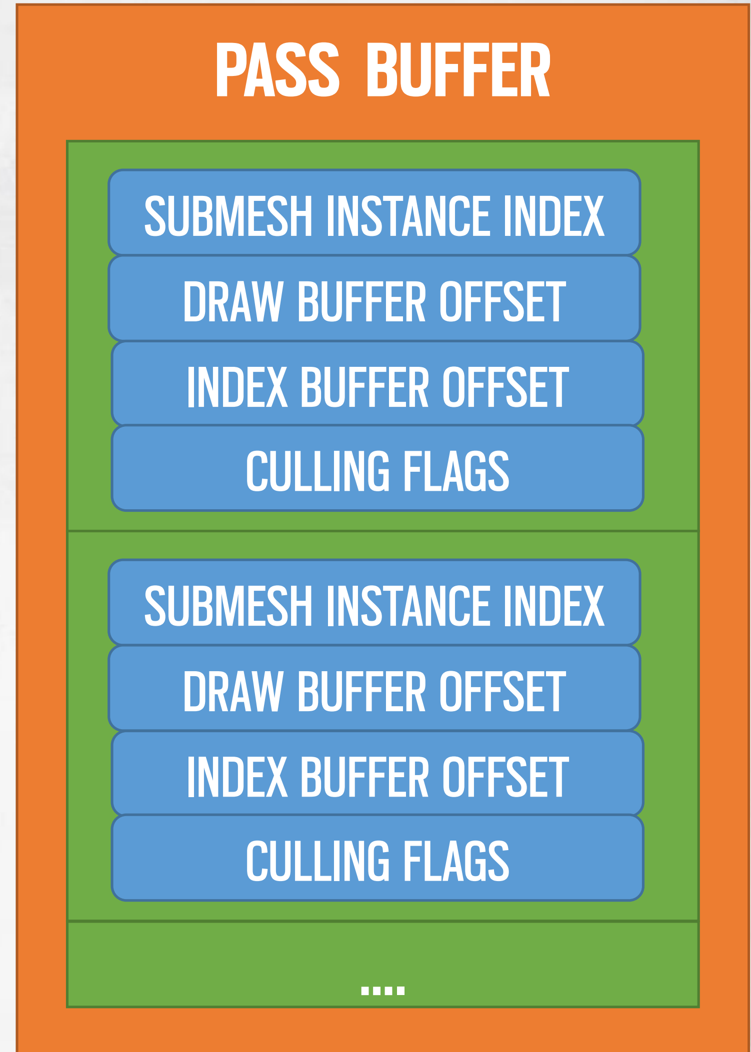
- Each submesh instance has a globally unique index:
  - Index used to fetch all data
  - Multiple indirection needed



GATHERING DRAW CALLS

- For each pass gather the submesh instance index into a dynamic buffer:
  - Each pass maps to one batch type exclusively
  - Buffer filled in multithreaded jobs (1.5ms linear)

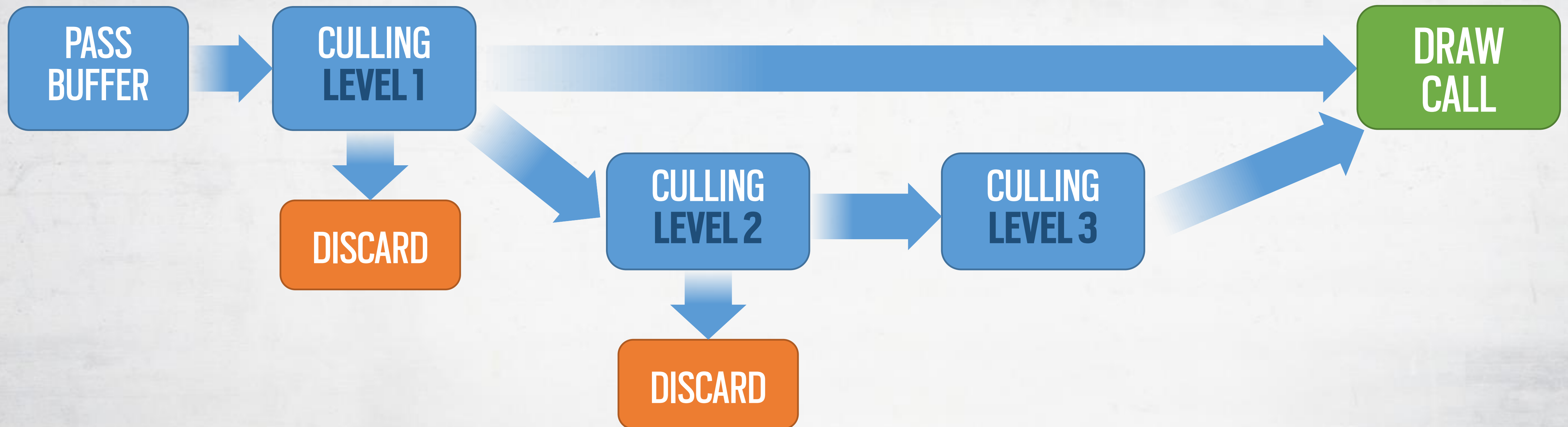
- Extra data to perform culling is added:
  - MultiDrawIndexedIndirect entry
  - New index buffer offset
  - Additional culling flags



PERFORMING CULLING

We define multiple types of culling:

- **Level 1:** Submesh instance culling
- **Level 2:** Submesh chunck culling
- **Level 3:** Submesh triangle culling



PERFORMING CULLING

LEVEL 1 CULLING

SCREEN SPACE SIZE CULLING

DISTANCE CULLING

FRUSTUM CULLING

OCCLUSION CULLING

LEVEL 2 CULLING

SCREEN SPACE SIZE CULLING

FRUSTUM CULLING

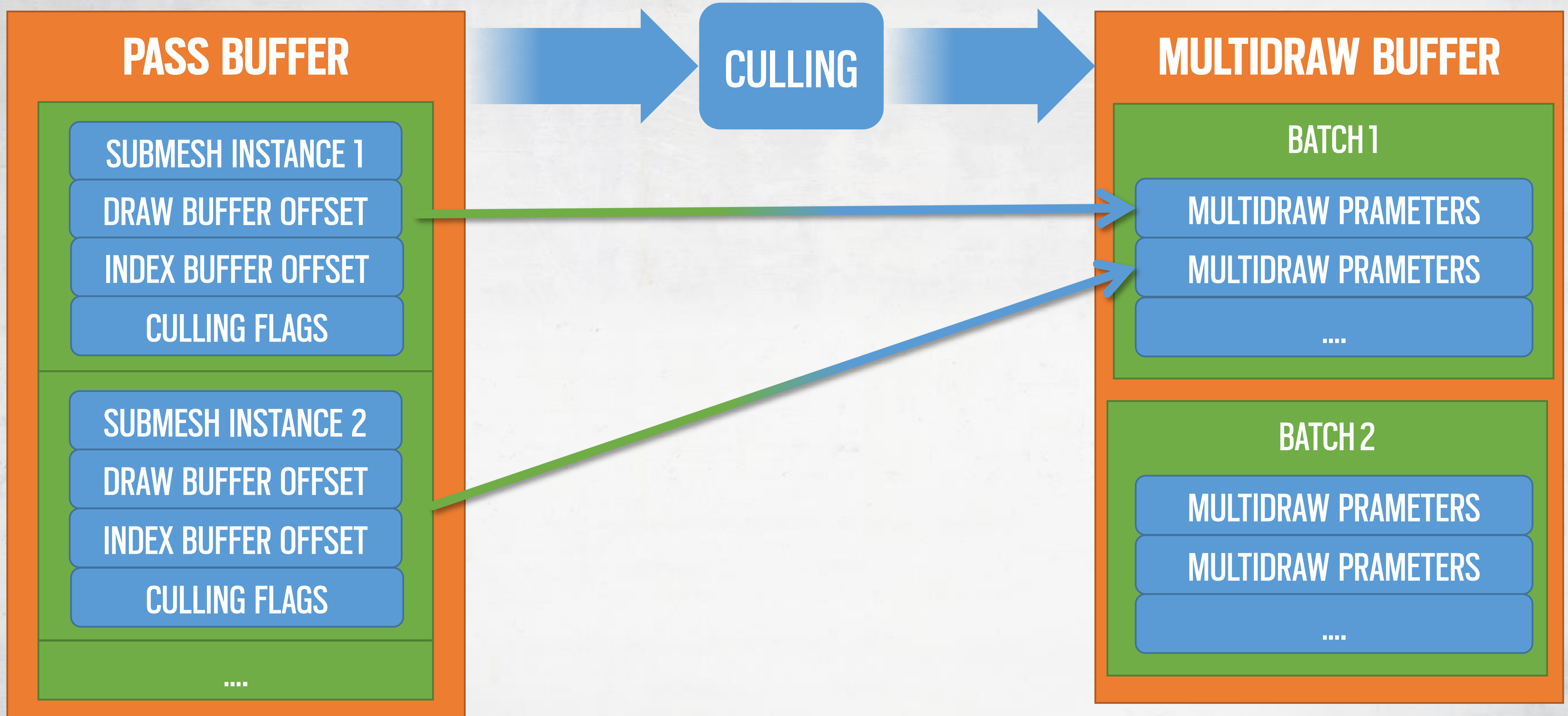
ORIENTATION CULLING

OCCLUSION CULLING

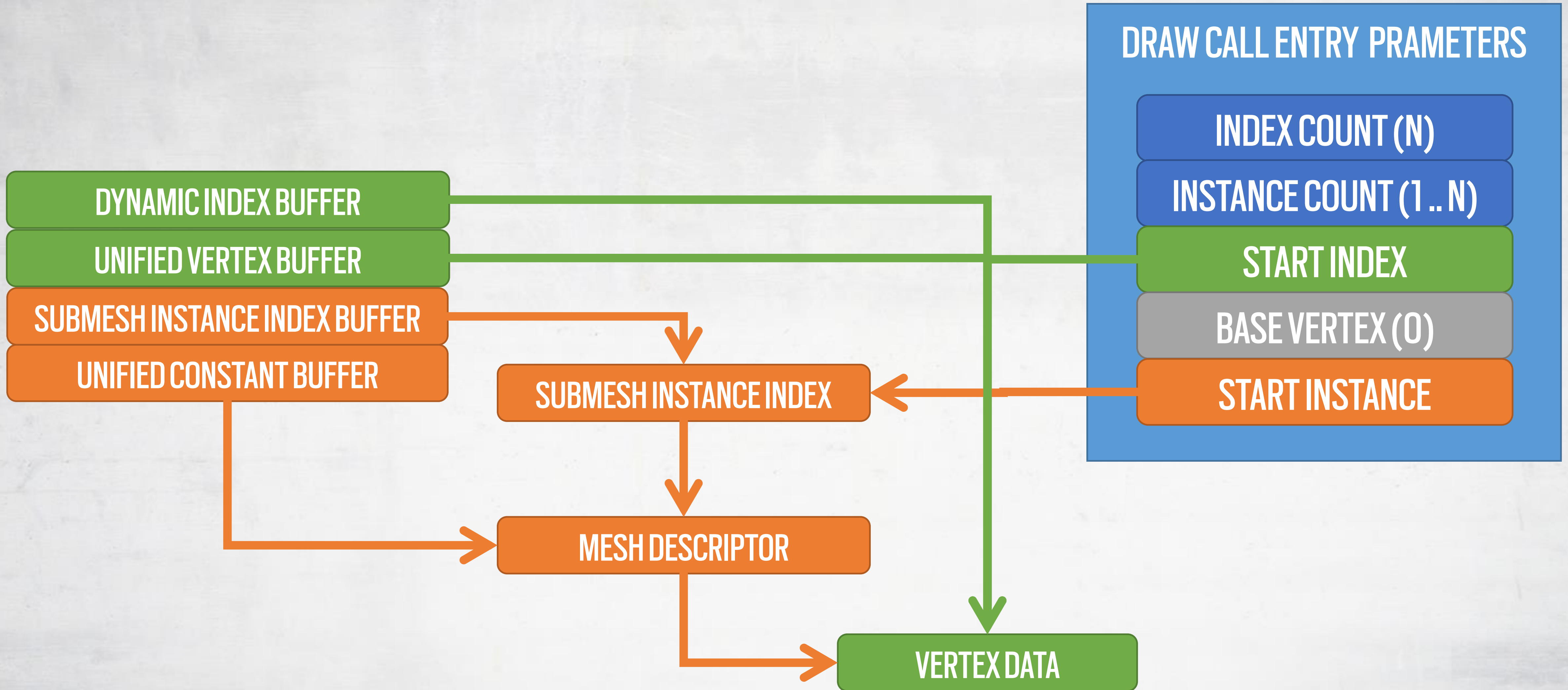
LEVEL 3 CULLING

TRIANGLE NORMAL CULLING

PERFORMING DRAW CALLS



PERFORMING A **DRAW CALL**



PERFORMING A **DRAW CALL**

Culling compute shader
writes out instance indices
in a Per Instance Buffer

```
struct VertexShaderInput
{
    uint PrimitiveInstanceIdx : PerInstanceInfo;
    uint VertexID             : SV_VertexID;
};

void GetVertexFromUnifiedBuffer(uint clusterFirstVertexOffset, uint vertexIdx, out UnpackedVertexFormat vertex)
{
    uint offset = clusterFirstVertexOffset + vertexIdx * VERTEX_FORMAT_STRIDE;
    vertex.Position = ToFLOAT3(g_VertexBuffer.Load3(offset + 0));
    vertex.Normal = ToUBYTE4(g_VertexBuffer.Load (offset + 12));
    vertex.TexCoord0 = ToFLOAT16_2(g_VertexBuffer.Load (offset + 16));
    vertex.VertexID = vertexIdx;
}
```

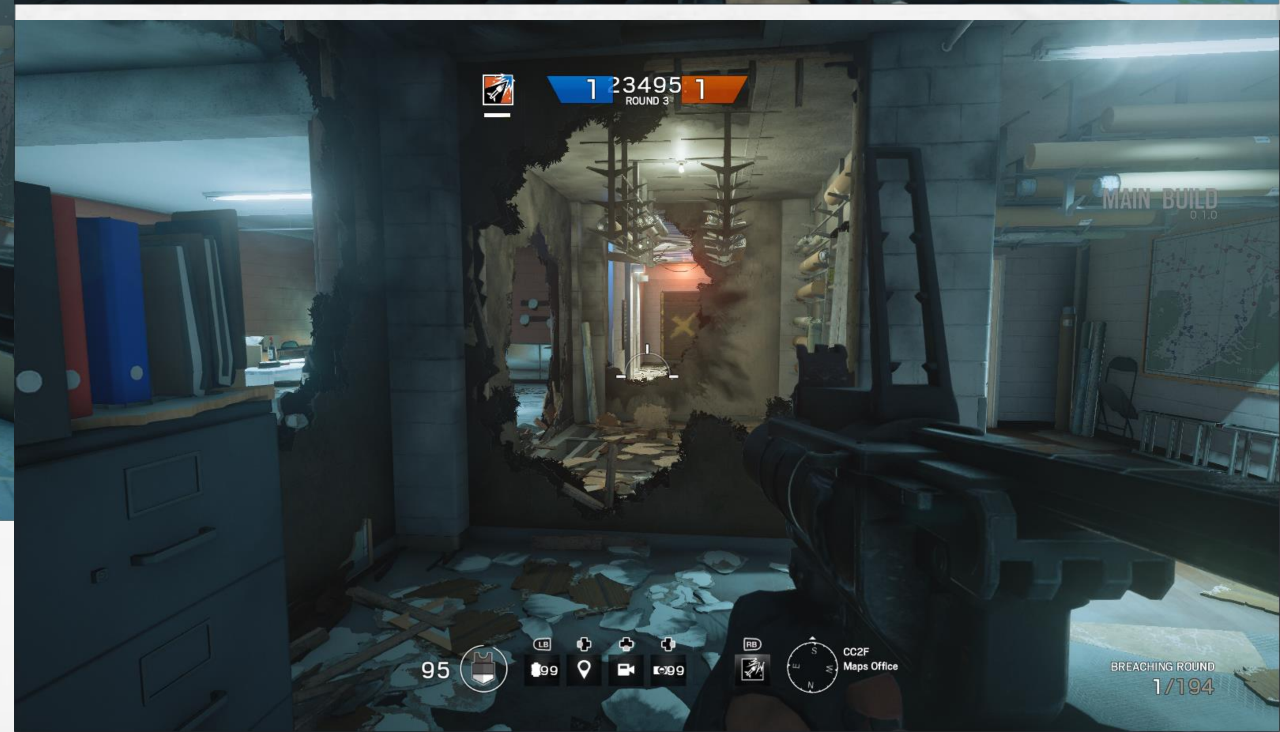
PERFORMING A DRAW CALL

ReadFirstLane is used in the pixel shader when loading UCB values with UnformsOffsets to be able to use the GCN scalar unit & registers

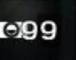
```
struct VertexShaderOutput
{
    ...
    nointerpolation uint4 UniformsOffsets;
}

VertexShaderOutput VSMain(VertexShaderInput input)
{
    LoadUniforms(input.PrimitiveInstanceIdx);
    UnpackedVertexFormat vfUnpacked;
    GetVertexFromUnifiedBuffer(g_ClusterFirstVertexOffset, input.VertexID, vfUnpacked);

    VertexShaderOutput vsOut;
    vsOut.UniformsOffsets = g_UniformsOffsets;
}
```

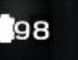
RAINBOW SIX DESTRUCTION

+5 DRAWCALLS



BATCH
VISUALISATION





BATCH VISUALISATION

Debug keys EXCLUSIVE

In(game) Host(game) NAT(unknown) Ping:0ms

0 23495 0
ROUND 1

MAIN BUILD
0.1.0

GRAB

100

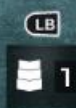
99 99 98

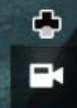
CG1F
Boat Garage

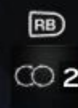
AR33
26/176

RESULTS

NUMBER OF UNBATCHED DC (TOTAL)	NUMBER OF BATCHED DCS (VIS + GBUFFER + DECALS)	NUMBER OF BATCHED DCS (SHADOWS)	CULLING EFFICIENCY
10537	412	64	73%







FUTURE WORK

- Pushing empty draw calls has a cost
  - We try to hide it on consoles using async jobs
  - Specifying the number of draw calls on the GPU would be the next step
- Using bindless resources to further batch draw calls
- Moving most of the scene graph traversal to the GPU
  - LoD selection logic

AGENDA

RAINBOW RENDERER OVERVIEW

MATERIAL BASED DRAW CALL SYSTEM

CHECKERBOARD RENDERING

60 FPS **MADE EASY**

- We wanted 60FPS early in production
  - First playable was running at around 50 on consoles
  - 60 FPS average was hit a couple weeks after!

- Killzone approach seemed like a good idea to start with (see [Valiant14])
  - Keeping nearly the same budget per pixel as a 30FPS game for screen pixels rendering
  - EQAA based, we wanted it on PC too (low end and 4K support)

- Big “quick” win without having a major quality impact
  - Silently enabled to see if people noticed

TEMPORAL INTERLACED **RENDERING**

- To target 1920x1080:
  - We render geometry and lighting to 960x1080 render target
- 3D velocity vector per rendered pixel
  - R12G12B8 format
- Projection matrix is offset each frame
- Need to divide x gradient by 2 to have similar texture filtering

```
float4 SampleTexture2D(Texture2D t, SamplerState s, float2 coord)
{
#if !INTERLACED_RENDERING
    return t.Sample(s, coord);
#else
    float2 dx = ddx(coord);
    float2 dy = ddy(coord);
    return t.SampleGrad(s, coord, dx/2, dy);
#endif
}
```

TEMPORAL INTERLACED **RENDERING**

- Things not represented by motion on screen need to be dealt with
  - Tried to maintain lighting/shadow changes to handle them better
  - Color clamping (See [Karis14])

- Data tweaked so alternating effects take place over at least two frames
  - Police car flash lights, light flickering
  - Flickering oscillators modified to avoid single frame 0 to 1 transitions

- Aliasing on vertical lines
- Not that easy after all!

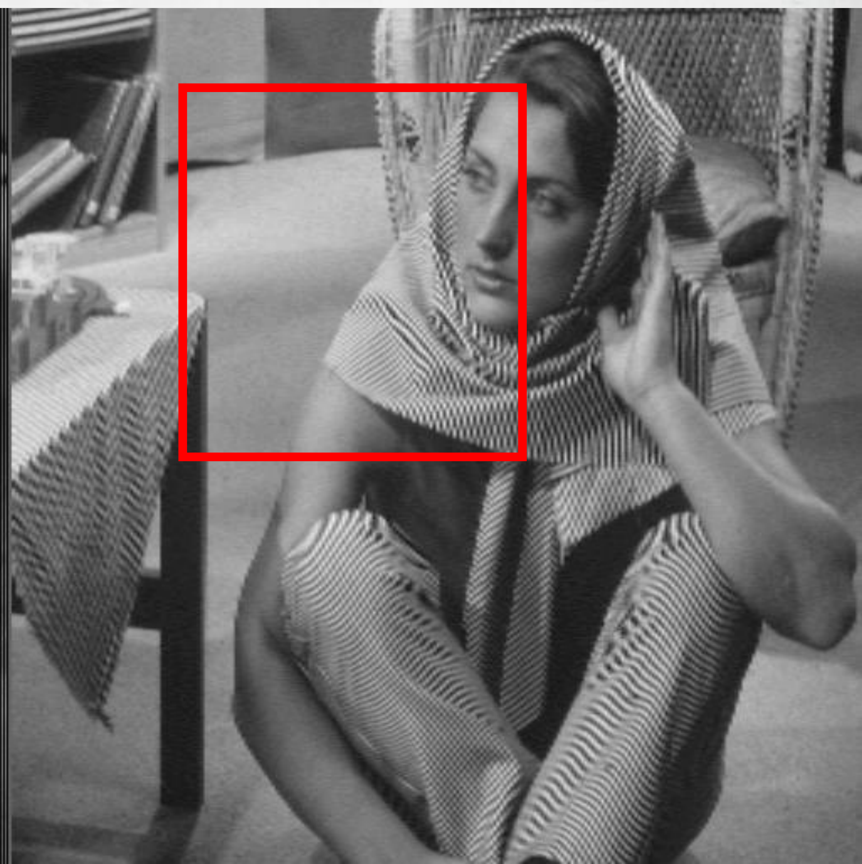
CHECKERBOARD RENDERING

- Base idea came about to solve aliasing issues
- Experimented on a series of images to first test quality
- For most images PSNR was better using a checkerboard pattern:
  - Visually the results were more pleasing too
- The idea of using MSAA 2X was bouncing around since the beginning
  - We made a push for it for E3 2015

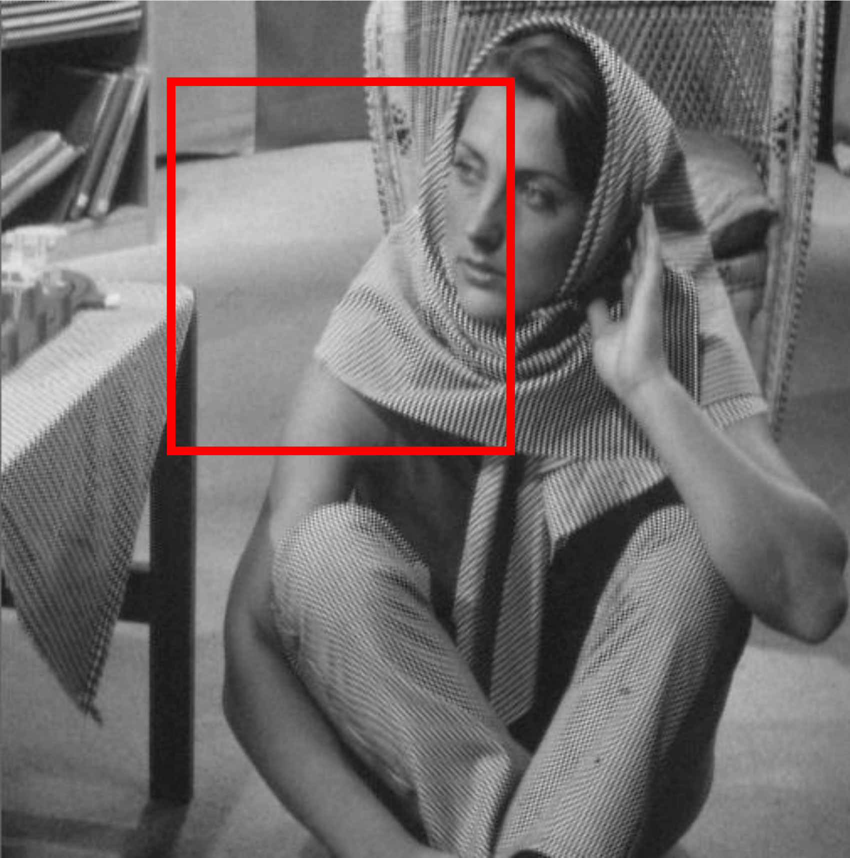
LINE NEIGHBORS INTERPOLATION

CHECKERBOARD NEIGHBORS
INTERPOLATION

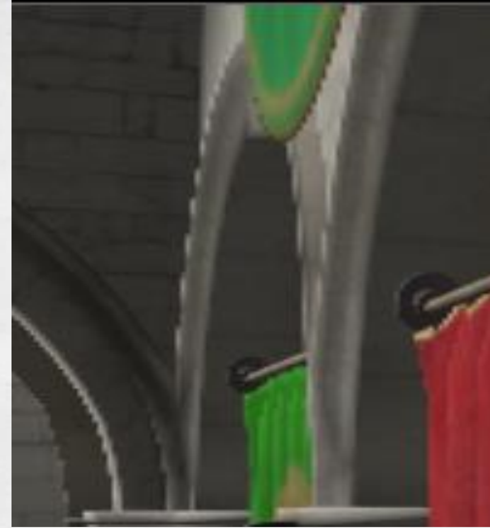
LINE NEIGHBORS INTERPOLATION



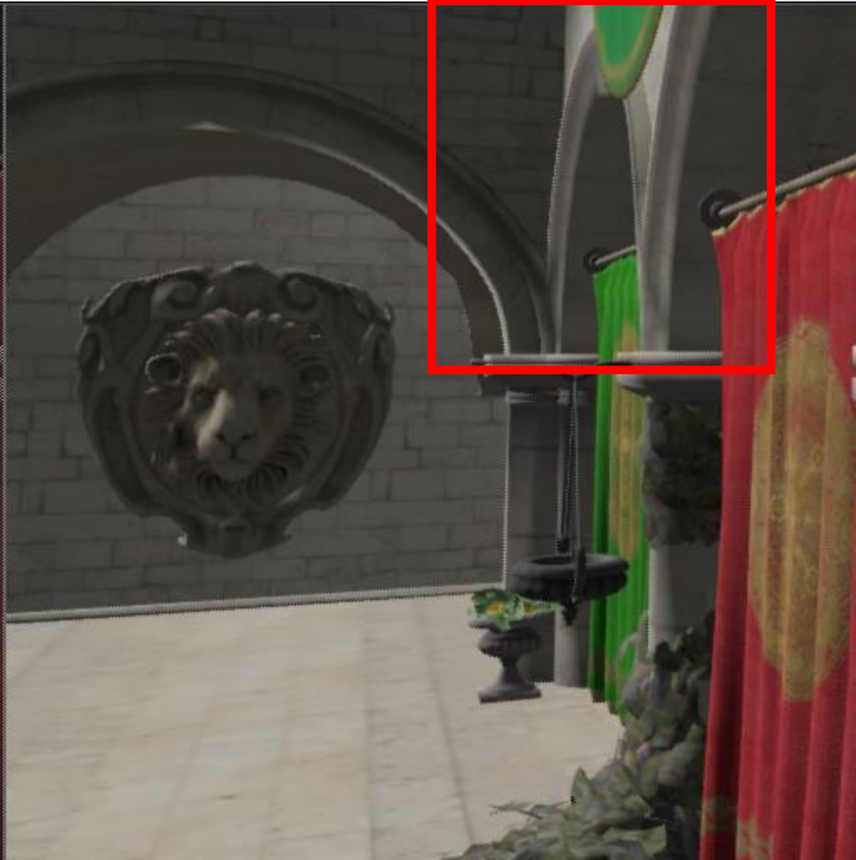
CHECKERBOARD NEIGHBORS
INTERPOLATION



LINE NEIGHBORS **INTERPOLATION**

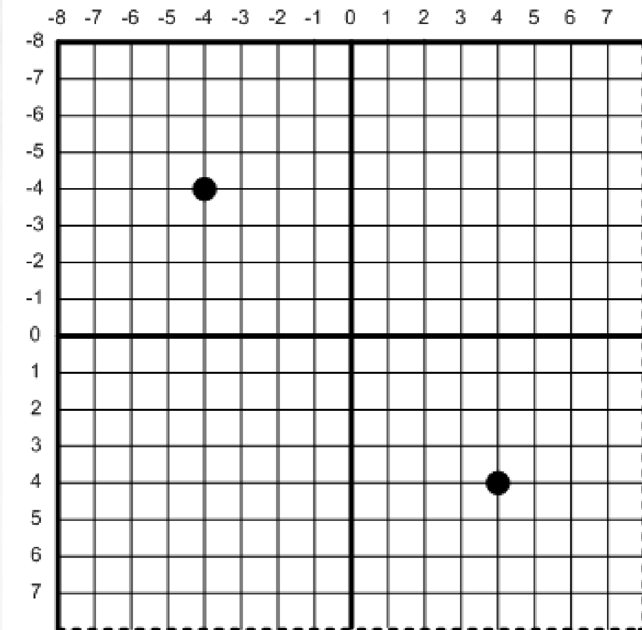


CHECKERBOARD NEIGHBORS
INTERPOLATION



CHECKERBOARD RENDERING **IMPLEMENTATION**

- Rendering to a ¼ size (½ width by ½ height) resolution with MSAA 2X:
  - We end up with half the samples of the full resolution image
- D3D MSAA 2X standard pattern
  - 2 Color and Z samples
- Sample modifier or SV_SampleIndex input to enforce rendering all sample
- Each sample falls on the exact pixel center of full screen render target

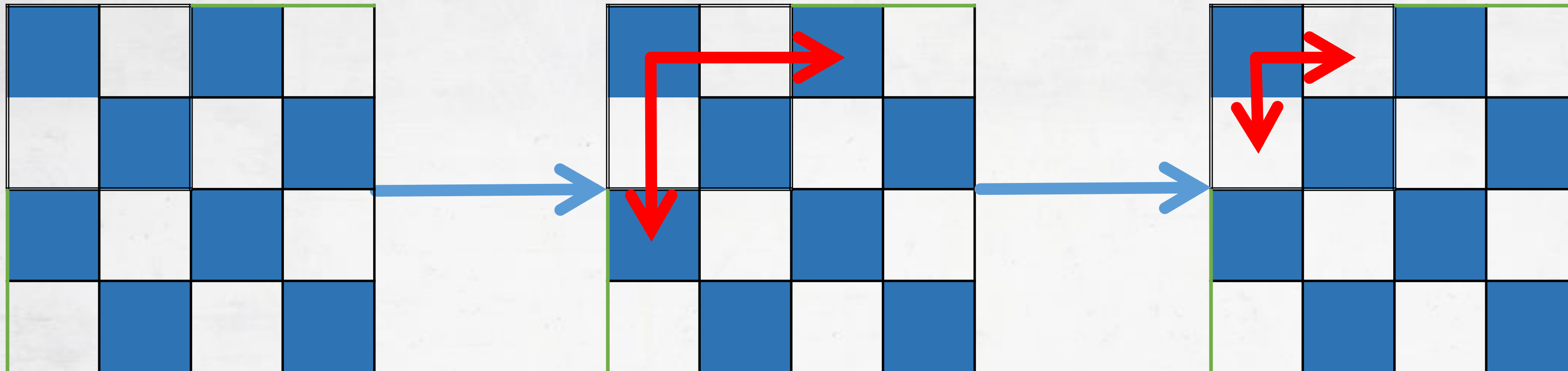


CHECKERBOARD **RENDERING BONUS**

- Particle effects can be easily evaluated per pixel instead of per sample
- You can fit a lot more stuff in ESRAM!
- No need to fixup gradients in the shaders!

CHECKERBOARD RENDERING **IMPLEMENTATION**

GRADIENT FIXUP



CHECKERBOARD RENDERING **IMPLEMENTATION**

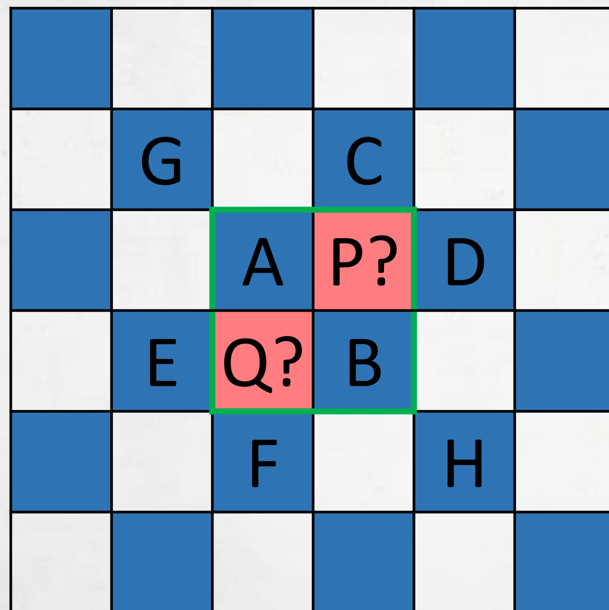
- By offsetting the projection matrix again each frame we are able to alternate the pattern
  - We don't always have access on PC to change sample locations

Even frames

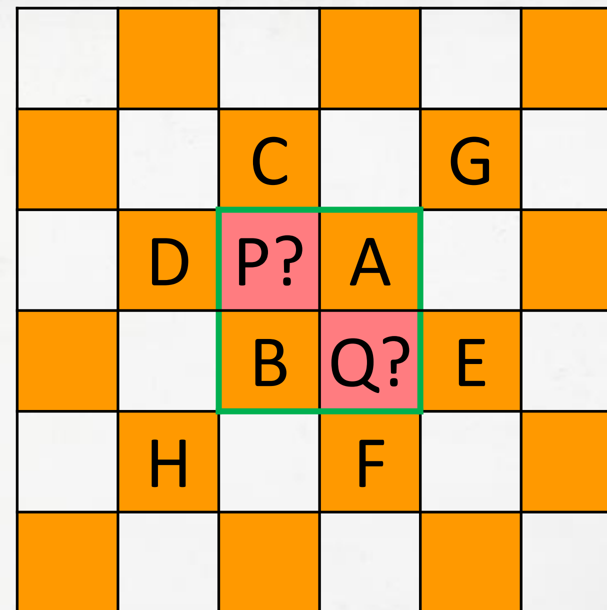
Odd frames

FILLING IN THE BLANKS

- To reconstruct colors for unknown pixels P and Q, we sample
  - Current frame direct neighbors linear-Z
  - Current frame direct neighbors color
  - History color and Z



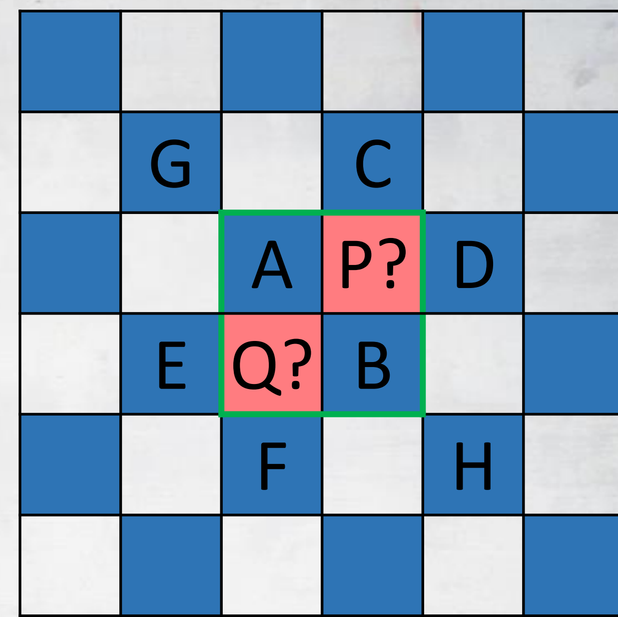
Even frames



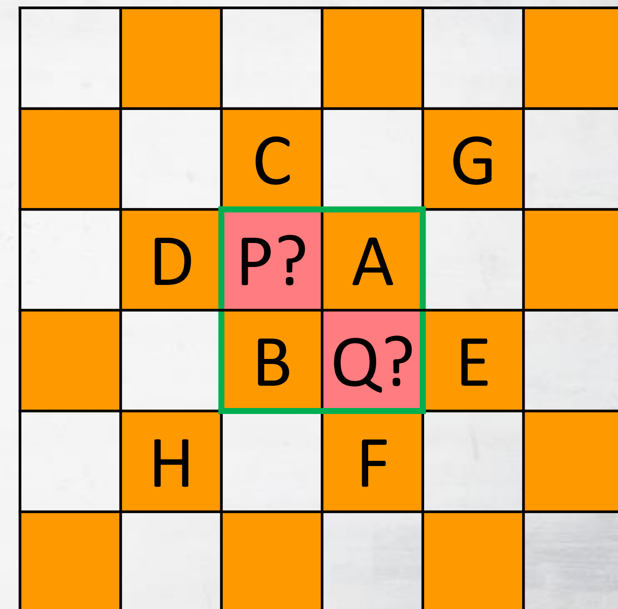
Odd frames

HISTORY COLOR/Z

- One neighbor gets picked for motion velocity:
  - Closest one to the camera to preserve silhouette
- With motion velocity we sample the previous resolved color
  - That way we get to use filtering, but introduces accumulation errors!
- We clamp the re-projected color with A B E F for Q
- Using previous depth computed from motion we compute a confidence value
  - Used to blend back toward the unclamped value.



Even frames

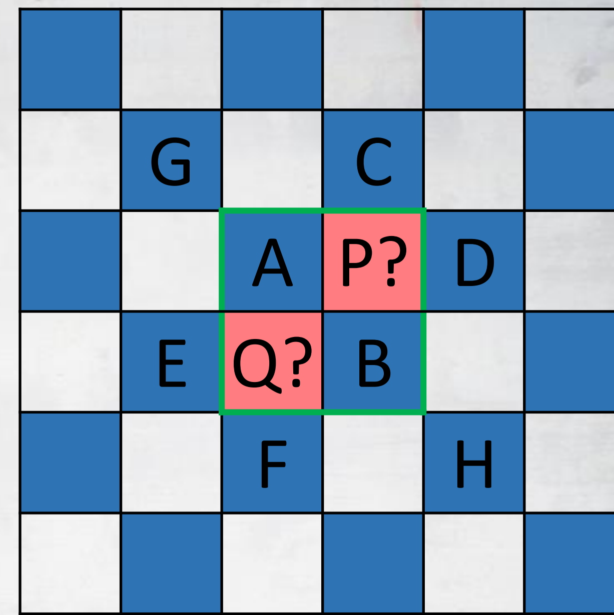


Odd frames

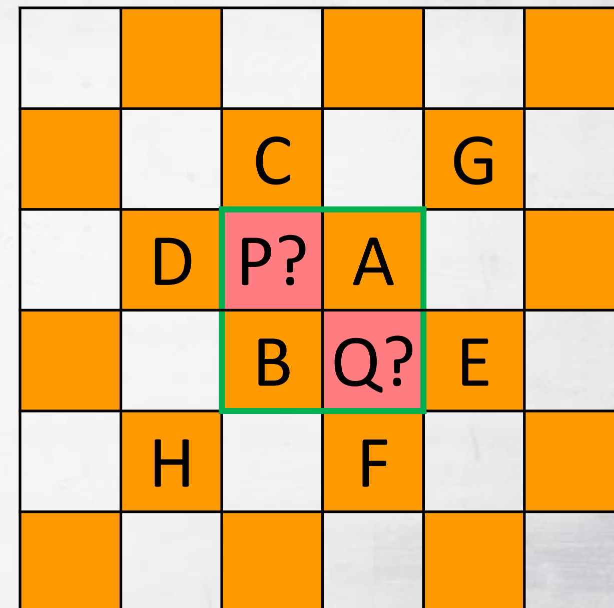
RESOLVED **COLOR**

- Having:
  - The history color
  - The interpolated color from direct neighbors

- A final color is computed using two additional weights:
  - Color coherency:
    - Minimum difference between A B E F for Q
  - Magnitude of velocity



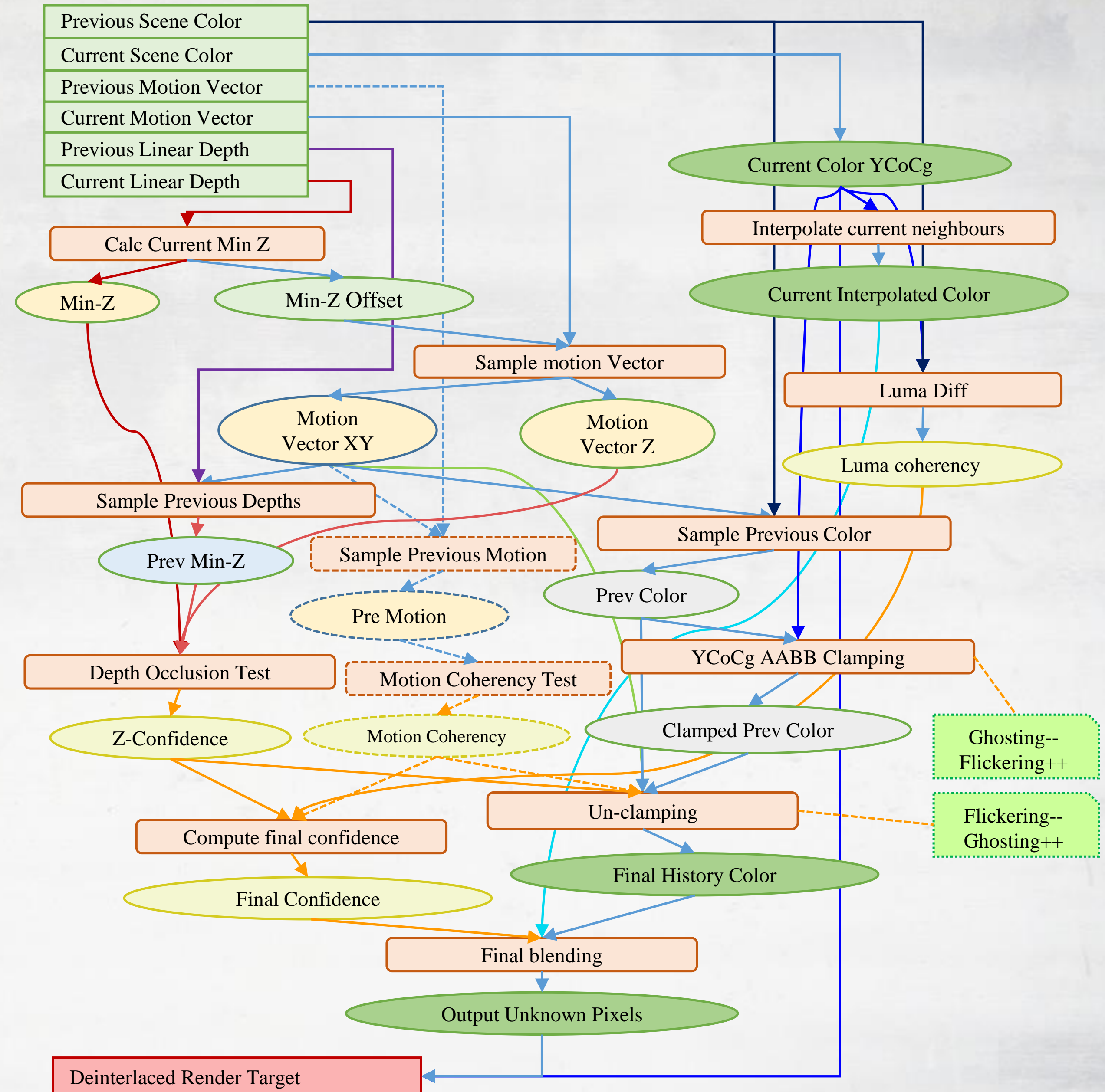
Even frames



Odd frames

COMPLETE FLOW

- Resolve quite complex
  - Lots of tweaks for our content!
- Costs 1.4ms
- 8 – 10ms net win



T-AA

- Integrates with the checkerboard rendering
  - Can be run on the same resolve shader
- Done on the sub-sample level, MSAA 4X style jitters on top of the checkerboard pattern
- Reprojectged color weight uses similar logic
- Additional “Unteething” used to remove bad checkerboard patterns

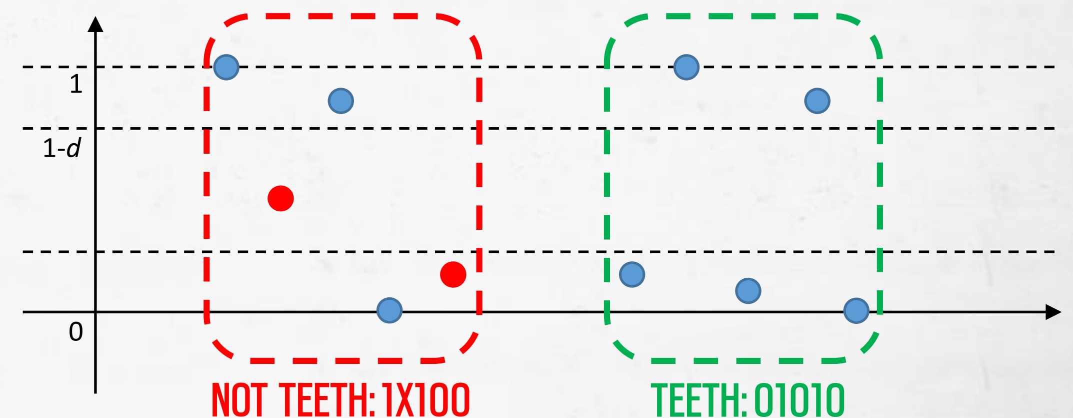
TEETH REMOVAL **FILTER**

- Resolve can introduce noticeable saw tooth patterns in the image
  - We apply a filter to remove them

- The filter works on 5 horizontally or vertically adjacent pixels

- We setup a threshold *d* and binaries pixel each to 0 or 1 if they fall in the range of $[0, d]$ or $[1 - d, 1]$

- We detect a 01010 or 10101 pattern



FUTURE DEVELOPMENTS

- Checkerboard technique was a good win for us
  - We are going to push more quality per pixel and build up on it
  - Implementation mostly by trial and error, we will move to a more scientific approach on the different confidence weights and values used

SPECIAL THANKS

- Alexandre Lahaise
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- Michel Bouchard
- Lionel Berenguier
- Paul Vlasie
- Stephen Hill
- Stephen McAuley
- Ulrich Haar

Thank you!

- ☑ RAINBOW RENDERER OVERVIEW
- ☑ MATERIAL BASED DRAW CALL SYSTEM
- ☑ CHECKERBOARD RENDERING

QUESTIONS?

REFERENCES

- Karis14: https://de45xmedrsdbp.cloudfront.net/Resources/files/TemporalAA_small-59732822.pdf
- Haar&Aaltonen15: http://advances.realtimerendering.com/s2015/aaltonenhaar_siggraph2015_combined_final_footer_220dpi.pdf
- Schulz14: http://www.crytek.com/download/2014_03_25_CRYENGINE_GDC_Schultz.pdf
- Valient14: http://www.slideshare.net/guerrillagames/killzone-shadow-fall-gdc2014-valient-killzonegraphics
- Hill11: http://blog.selfshadow.com/publications/practical-visibility/
- Intro video by 20Powerproductions : https://www.youtube.com/watch?v=RcOV98BzW3g
- Icons by FLATICON.COM

BONUS SLIDES

GBUFFER LAYOUT

4 Render Targets (RGB10A2 + 3 * RGBA8) + Depth sStencil (D32 – S8)

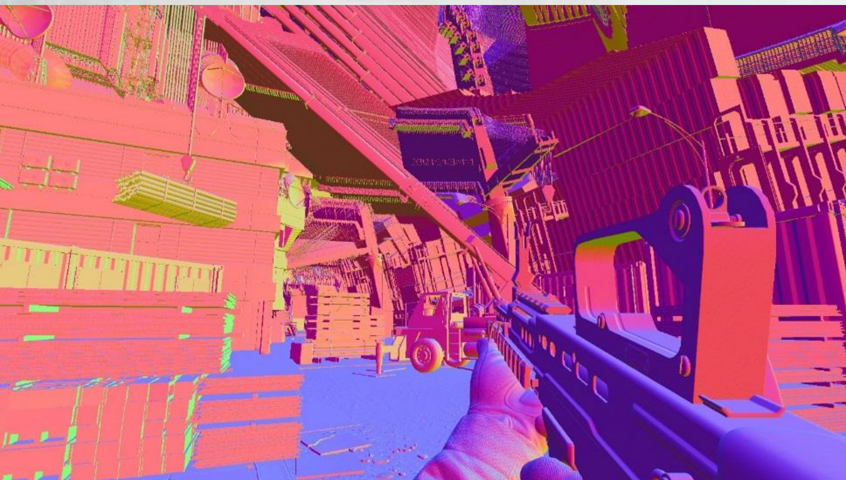
R	G	B	A
World Normal (RGB10)			GI Normal Bias (A2)
BaseColor (sRGB8)			Config (A8)
Metalness (R8)	Glossiness (G8)	Cavity (sB8)	Aliased Value (A8)
Velocity.xy (RGB8)			Velocity.z (A8)

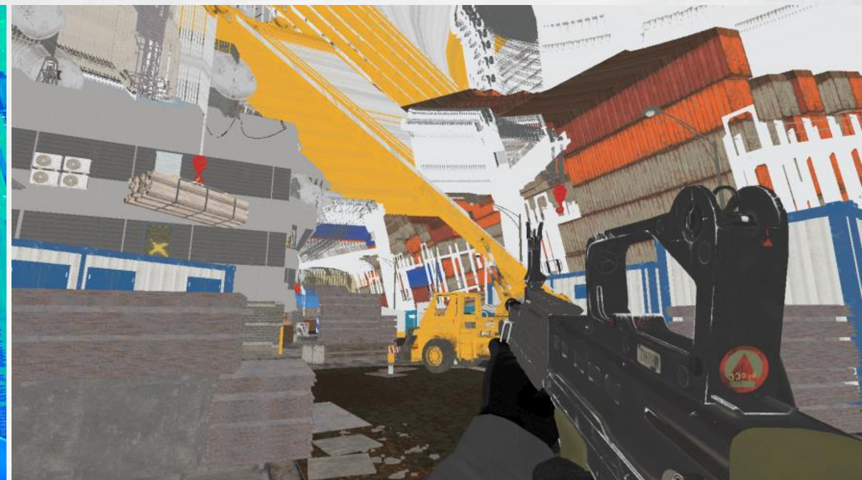
CONFIG	ALIASED VALUE
Default	Self AO (sA8)
Skin	Skin SSS Mask (sA8)
Translucent	Translucence (sA7) + Back Face (A1)

GBUFFER RENDERING

- We use inverted depth combined with a D32 float for better uniform depth precision distribution
- For normals we experimented with BFN first
  - We moved to a R10G10B10A2 format to save VGPRs and ALU
- Velocity vector is 3D and enjoys a higher precision on the X & Y axis to support our temporal reprojection rendering
- GBuffer Layer 2's alpha is aliased depending on the material type
  - Self-AO was not used since SSBC revealed itself sufficient most of time
  - We apply a higher SSAO factor on the first person character

GBUFFER RENDERING





LIGHTING - GI

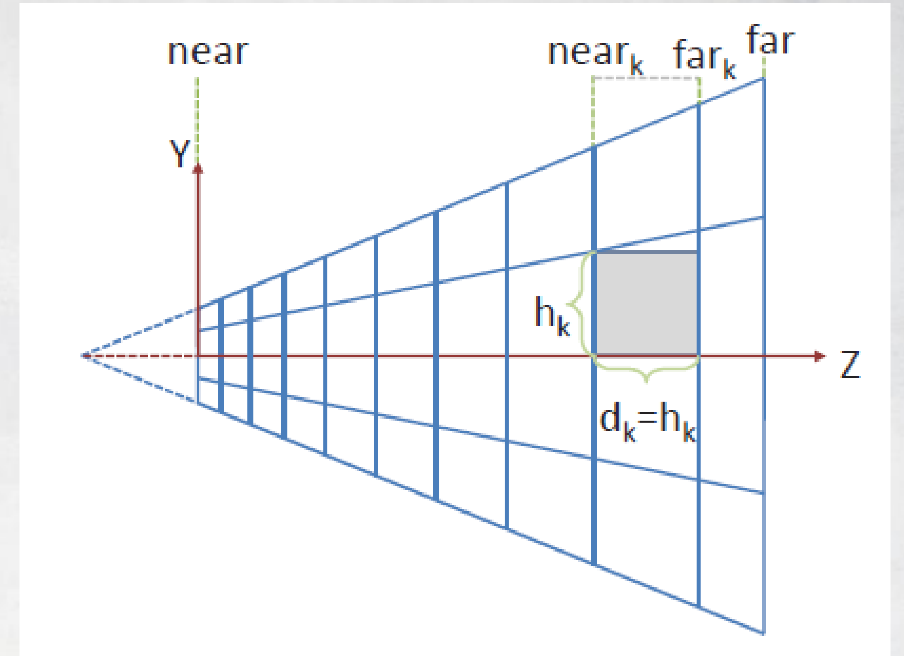
- GI is static and is based on a simplification of Assassin's Creed Unity GI
  - Low resolution volume covering whole map:
    - Sky visibility SH
    - 1m to 2m per voxel
  - High resolution volume covering the playable area:
    - Sky visibility SH
    - Bounce color SH
    - 25cm per voxel

Screenshot of low res Volume

Screenshot of high res Volume

LIGHTING – DIRECT

- We generate a clustered structure on the frustum:
  - 32x32 pixels based tile
  - Z exponential distribution
  - Hierarchical culling of light volume to fill the structure



- Light cookies (gobos) are gathered in an array to be able to fetch them dynamically
  - Simply part of the light data as indices in an array

LIGHTING – SSR

- Done in ¼ resolution
- Uses face normal to give ray direction
- Temporal reprojection with light accumulation (ray-based, not depth based)
- Linear marching, steps gloss dependent
  - Jitter start ray position and direction
  - Temporal reprojection smooth the results
- Invalidate previous frame result on camera movement

LIGHTING – REFLECTION

- Local cubemaps
  - Parallax corrected
  - Regarded as lights, volume injected in clustered lighting structure
  - Reside in cubemap array for easy access

- Cubemaps applied during SSR application
  - Local cubemaps are SSR's primary fallback
  - Global cubemap is secondary fallback

LIGHTING – FORWARD

- Support same set of features as the deferred pass:
  - All shadows, cubemaps, cookies are in texture arrays

- VGPR consumption issues:
  - Scaling down on the quality of shadow filtering
  - Glass disables some lights types
  - Still lowest occupancy in our renderer

- Expensive particles use the ESM version of the shadow cache

SCHEDULING

- Graphic thread managing work queues and stealing work when necessary, work stolen gets executed on the immediate context when possible to minimize overhead.
- On PC no draw calls are recorded we let the material based draw call pipeline handle the scaling.
- On consoles graphics work has priority on Cluster 0 – Core 0, 1, 2 and we also maintain cluster locality when scheduling tasks.
  - Fork & join work can take a turn for the worst when hammering shared atomics. (add numbers)

SCHEDULING

- Rendering-specific scheduler on top of the engine scheduler:
  - Full control of graphic task behavior to fit in our budgets
  - Task dependencies code defined
    - Investing on visualisation tools would have been worth while

  - First implementation used system fibers
    - Workers can steal a job with more priority instead of waiting
    - Fibers confusing to programmers
    - Some systems have trouble displaying them properly in the debugger

  - We moved to a simpler model where yielding just executes a new job on the current context

GRAPHIC CPU PERFORMANCES **ON RAINBOW**

- Beside from initialization, zero tolerance global allocator usage during the frame
  - Heavy use of per worker thread local allocator
    - Resets when outermost job finishes
    - Helps on cache locality and more flexible
  - Heavy use of pooling
    - Dangling pointers becomes harder
    - Adding memory state values on builds to check validity

- Memory access patterns were 95% of the optimization works on the graphic side
  - Per thread gather lists are used to decrease inter thread communication
  - Atomics have an important cost if not used properly

SLI SUPPORT

- Driver tracking disabled on all resources
- Simple scoping interface for update of resources that need sync
  - One line addition to the code when necessary
- Update of a couple of large buffers was implemented by propagating the changes manually on each GPU
  - A lot more efficient than synching buffers
  - Update of unified constant buffers takes a couple of μs, copy brakes scaling